UNIVERSITI PUTRA MALAYSIA

EFFECTS OF GRAIN REFINEMENT ON THE COOLING RATE, AND MICROSTRUCTURAL AND MECHANICAL PROPERTIES OF AL-SI SAND CASTINGS

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By

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This thesis covers the key areas of numerical simulation of sand casting process to evaluate the runner and gating system of sand mold. The major experimental work is focused on grain refinement and modification of LM6 Al-Si sand casting. The simulation software package used is MAGMAsoft and the sand casting process employed is CO_2 sand casting. The numerical results of MAGMAsoft match qualitatively with the experimental data. This validates the use of MAGMAsoft to simulate sand casting process to assist in mold design and prediction of flow and solidification characteristics.

The implementation of experimental work to ascertain flow and solidification characteristics of sand casting has been performed on a casting designed with varying thickness of different moduli. The casting metal used is LM6 Al-Si alloy. The cooling rate of sand casting has been correlated with the modulus of casting. The mechanical

mechanical properties of hardness and ultimate tensile strength have been correlated with the solidification rate. The secondary dendrites arm spacing (SDAS) is also found to have linear correlation with section modulus. This provides important and useful information to product design of sand casting about how to optimize the section thickness to achieve the desired mechanical properties.

An investigation is carried out to study how to further enhance the mechanical properties of LM6 Al-Si alloy sand casting by adding the commercial grain refiner of Al-5Ti-1B into the melt at different inoculation levels of 0.25, 0.5, 0.75 and 1.0% weight. The results show that 0.5% weight of Al-5Ti-1B grain refiner is the optimal level to grain refine and enhance the mechanical properties of LM6 sand casting. The microstructural analysis shows that grain size is reduced when the casting solidifies with faster cooling rate due to the addition of grain refiner. This renders significant effect to enhance the mechanical properties of the casting. The improvement of grain refinement is quantified by measuring the hardness, ultimate tensile strength (UTS) and elongation (strain) of the cast samples. Inoculation with 0.5% weight of Al-5Ti-1B grain refiner has attained UTS of 167.86 MPa, maximum hardness of 65.6 Rockwell and fracture strain of 0.0314. A further investigation has been carried out to add 0.5% weight of Al-10Sr and 0.5% weight of Al-5Ti-1B into the melt to cast the same part. Similar mechanical tests and microstructural analysis are performed to study the combination effect of strontium, titanium and boron on LM6 sand castings. It is discovered that the ultimate tensile strength of the castings is further improved to 174.46 MPa and the morphology has been modified. However, the hardness of Sr-modified LM6 sand casting only achieves a maximum value of 63.34 Rockwell which is not a significant improvement. Modification of LM6 by strontium only alters the morphology of the silicon eutectic to be more fibrous instead of acicular so that the structure would not be brittle relative to unmodified structure and it is found that the ductility after modification achieves a fracture strain of 0.032 which is higher than the 0.0267 of unmodified LM6. The cooling curve shows that the solidification is dramatically transformed to eutectic solidification at temperature around 540 ^{o}C. This mixture of grain refiner and modifier is termed "*hybrid modifier*" by the author.

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KESAN PENGHALUSAN BUTIRAN KE ATAS KADAR PEMBEKUAN DAN SIFAT-SIFAT MIKROSTRUKTUR DAN MEKANIKAL TUANGAN PASIR Al-Si

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Tesis ini merangkumi bidang simulasi numerikal untuk proses penuangan acuan pasir untuk menilai sistem larian dan get bagi acuan pasir. Ujikaji yang diberi tumpuan utama ialah penghalusan saiz butiran mickrostruktur dan modifikasi mikrostruktur bagi produk tuangan acuan pasir LM6 Al-Si. Perisian simulasi yang digunakan ialah MAGMAsoft dan proses penuangan acuan pasir ialah proses karbon dioksida. Keputusan numerikal MAGMAsoft dibandingkan secara kualitatif dengan data ujikaji menunjukkan mereka sepadan. Ini mengesahkan penggunaan MAGMAsoft untuk simulasi proses penuangan acuan pasir dapat membantu rekabentuk acuan dan meramalkan sifat pengaliran dan pembekuan proses tersebut.

Pelaksanaan kerja ujikaji untuk mengkaji proses pengaliran dan pembekuan acuan pasir telah dilakukan ke atas satu tuangan yang direkabentuk dengan ketebalan yang berbeza, iaitu modulus setiap keratannya berlainan. Bahan logam untuk tuangan

ialah aloi aluminium-silikon LM6. Kadar pembekuan tuangan telah dihubungkait dengan modulus keratannya. Sifat mekanikal seperti kekerasan dan kekuatan tegangan muktamad juga dihubungkait dengan kadar pembekuan. Jarak sekundar antara dendrit (SDAS) juga didapati mempunyai korelasi linear dengan modulus keratan. Ini memberikan maklumat yang penting dan berguna untuk rekabentuk acuan pasir supaya dapat mengoptimumkan modulus keratan demi mencapai sifat mekanikal yang dikehendaki.

Satu kajian telah dijalankan untuk mengkaji bagaimana memperbaiki sifat mekanikal aloi LM6 dalam tuangan acuan pasir secara menambahkan penghalus butiran mikrostruktur Al-5Ti-1B ke dalam peleburan pada peratusan berat 0.25, 0.5, 0.75 dan 1.0. Keputusan ujikaji menunjukkan peratusan berat sebanyak 0.5 Al-5Ti-1B adalah tahap yang optimum untuk menghaluskan saiz butiran mikrostruktur dan memperbaiki sifat mekanikal tuangan LM6. Analisis mikrostruktur menunjukkan saiz butiran mikrostruktur berkurang bila tuangan membeku dengan kadar yang lebih cepat akibat penambahan penghalus butiran mikrostruktur tersebut. Ini memberi kesan yang ketara dalam pembaikan sifat mekanikal tuangan. Penambahbaikan penghalusan saiz butiran mikrostruktur dinyatakan secara pengukuran kekerasan, kekuatan tegangan muktamad (UTS) dan keterikan sampel-sampel yang dihasilkan. Inokulasi dengan 0.5% keberatan Al-5Ti-1B penghalus butiran mencapai UTS 167.86 MPa, kekerasan maksima 65.6 Rockwell dan keterikan patah 0.0314. Penyelidikan lanjut dijalankan dengan menambahkan Al-10Sr dan Al-5Ti-1B sebanyak 5 peratus keberatan masing-masing ke dalam peleburan untuk membuat tuangan yang sama. Ujian mekanikal dan analisis mikrostruktur yang sama dijalankan untuk mengkaji kesan penggabungan antara strontium, titanium dan boron ke atas tuangan LM6. Adalah didapati kekuatan tegangan muktamadnya meningkat ke 174.46 MPa dan bentuk mikrostrukturnya telah diubah. Walaubagaimanapun, kekerasannya hanya mencapai Nilai maksiam 63.34 Rockwell dan tidak menunjukkan kesan pembaikan yang ketara. Modifikasi LM6 dengan strontium hanya mengubah morfologi eutektik silicon kepada bentuk yang lebih halus dan bukan berbucu tajam supaya strukturnya tidak rapuh jika dibanding dengan structure yang tidak diubah; adalah didapati kelenturan selepas modifikasi mencapai keterikan patah 0.032 yang lebih tinggi daripada 0.0267 yang didapati pada LM6 asal. Graf suhu pembekuan menunjukkan proses pembekuan telah berubah kepada pembekuan eutektik pada suhu kira-kira 540°C. Campuran penghalus butiran mikrostruktur dan pengubah itu dinamakan sebagai "*hybrid modifier*".

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I certify that an Examination Committee has met on 3rd January 2006 to conduct the final examination of Lim Ying Pio on his Doctor of Philosophy thesis entitled "Effects of Grain Refinement on the Cooling Rate, and Microstructural and Mechanical Properties of Al-Si Sand Castings" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

LIM YING PIO

Date: 28/02/ 2006

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LIST OF ABBREVIATIONS

C, C_o	Alloy composition
C_v	Specific heat at constant volume, ($J.kg^{-1}.K^{-1}$)
D	Species diffusivity ($m^2.s^{-1}$)
E	Internal energy (J/mole or J/m^3)
G	Gibbs free energy (J/mole or J/m^3)
H	Enthalpy (J/mole, J/m^3, J/kg)
P	Pressure (Pa)
R	Gas constant (J/mol/K)
T	Temperature (K or ^oC)
T_L	Liquidus temperature (K)
T_S	Solidus temperature (K)
S	Entropy ($J.mol^{-1}.K^{-1}$ or $J.m^{-3}.K^{-1}$)
v	Velocity (m/s)
c	Specific heat ($J.m^{-3}.K^{-1}$)
f	Mass fraction of phase
g	Volume fraction of phase
	Gravitational acceleration ($m.s^{-2}$)
h	Heat transfer coefficient ($W.m^{-2}.K^{-1}$)
k	Solute partition coefficient; Thermal conductivity ($W.m^{-1}.K^{-1}$)
m	Slope of liquidus line ($K.wt\%^{-1}$)

n	Number of atoms (moles)
t	time
V	volume (m^3)
ΔG_v	change in volumetric free energy ($J.m^{-3}$)
L, H_f	latent heat of fusion ($J.kg^{-1}$)
ΔT	Undercooling (K)
Γ	Gibbs-Thomson coefficient (m.K)
α	Thermal diffusivity ($m^2.s^{-1}$)
β_T	Thermal expansion coefficient (K^{-1})
μ	Dynamic viscosity ($N.m^{-2}.s$)
ε	Cooling rate (K/s)
λ	Interphase spacing (m)
Ω	Spatial volume
γ	Surface tension (N/m)
	Subscript
L	Liquid
S	Solid
f	Fusion
k	Kinetic

CHAPTER 1

INTRODUCTION

1.1 Introduction

Metal casting is basically a process in which molten metal is poured by gravity or injected with pressure into a mold cavity to produce the desired product. Most of the cast products are in finished goods form which requires minimum level of machining and surface finishing to achieve the desired tolerance and surface quality. The casting process often involves flow which is usually transient and non-isothermal with ongoing solidification as the molten material flows through the mold [1]. Many industrial parts and components are produced by the method of casting, including engine blocks, crankshafts, automotive components, railroad equipment, plumbing fixtures, power tools, very large components for hydraulic turbines and so on [2]. Most of the casting operations are carried out in foundries. Foundry operations involve two major separate activities for the manufacture of casting products. The first activity is pattern and mold making, traditionally performed manually by experienced workers, which now regularly utilize computer-aided design and manufacturing and rapid prototyping techniques in modern manufacturing environment. The approach of advanced manufacturing techniques such as CAE and rapid prototyping is vital to minimizing trial-and-error operations which is time